Sensitivity of MODIS 2.1-μm Channel for off-nadir View Angles for use in Remote Sensing of Aerosol

C.K. Gatebe[1], M.D. King[2], S.-C. Tsay[3], Q. Ji[4] and T. Arnold[5]

[1]USRA, NASA/Goddard Space Flight Center, Code 913, Greenbelt, Maryland 20771
[2]NASA/Goddard Space Flight Center, Code 900, Greenbelt, MD 20771
[3]NASA/Goddard Space Flight Center, Code 910, Greenbelt, MD 20771
[4]SSAI, NASA/Goddard Space Flight Center, Code 913
[5]SM&A, NASA/Goddard Space Flight Center, Code 913

ABSTRACT – In this sensitivity study, we examined the ratio technique, the official method for remote sensing of aerosols over land from Moderate Resolution Imaging Spectroradiometer (MODIS) DATA, for view angles from nadir to 65° off-nadir using Cloud Absorption Radiometer (CAR) data collected during the Smoke, Clouds, and Radiation–Brazil (SCAR-B) experiment conducted in 1995. For the data analyzed and for the view angles tested, results seem to suggest that the reflectance $\rho_{0.47}$ and $\rho_{0.67}$ are predictable from $\rho_{2.1}$ using: $\rho_{0.47} = \rho_{2.1}/6$, which is a slight modification of Kaufman et al. (1997) and $\rho_{0.67} = \rho_{2.1}/2$, similar to Kaufman et al. (1997). These results hold for target viewed from backscattered direction, but not for the forward direction.

INTRODUCTION

Aerosols exhibit high spatial and temporal variability making it difficult to characterize them solely on the basis of sporadic *in situ* measurements (Husar *et al.*, 1997). For that reason, satellite remote sensing is gaining worldwide recognition as a method best suited for characterizing aerosols on A global scale because of their wide spatial coverage. Measurements of the radiative and microphysical properties of aerosols are derived using many different methods, including single- and multiple-channel reflectance, multiangle reflectance, contrast reduction, and polarization. A summary of these techniques is given in King et al. (1999).

In remote sensing of aerosols, differential spectral responses across the solar spectrum and correlations between spectral bands have been exploited in derivation of aerosol optical properties (Fraser et al., 1984; Kaufman et al., 1990; Ferrare et al., 1990). In an attempt to reduce surface effects, Kaufman and Sendra (1988) suggested a "dark surface target" approach, the ratio technique, to retrieve aerosol in regions where the surface is covered with dense vegetation or forest. One advantage of the ratio technique is that the surface reflectance is small, so that the error in retrieved aerosol optical thickness is also relatively small compared to errors over bright surfaces. Another advantage of using the dark target approach is that there is a correlation between the mid-IR band at 2.1 μm and visible (blue and red) bands. Hence, the mid-IR band at 2.1 μm may be used to estimate the surface reflectance in the blue and red bands, and further to infer aerosol optical thickness in the two bands (Kaufman et al., 1997). Detecting dark surface targets using 2.1 μm instead of 3.75 μm is much more efficient. The advantage of the 2.1 μm channel is that it is not affected by emitted radiation, and is much larger than the size of most aerosol types (e.g. smoke, sulfates, etc), except dust, so that these aerosols are transparent to solar radiation at 2.1 μm. Unlike emission corrections, there is much greater certainty in correcting for the effect of water vapor absorption once the amount of water vapor in the column is measured from the same satellite. On the other hand, the 3.75 μm channel is not affected by accumulation mode aerosol, e.g., sulfates and organic particles, though it is affected by dust.

In this sensitivity study, we examine the effect of the ratio technique for off-nadir viewing angles using data taken with the Cloud Absorption Radiometer (CAR) during the Smoke, Clouds, and Radiation–Brazil (SCAR-B) experiment conducted in 1995. Variations of view angle across images and between images occur naturally due to a wide swath width (as for the Advanced Very High Resolution Radiometer (AVHRR) or Moderate Resolution Imaging Spectroradiometer (MODIS) or to along the track off-nadir viewing capabilities (as for the along-track scanning radiometer (ATSR-2) or MISR). As an example, MODIS images the Earth's surface across track with a swath width of 2330 km (Running et al., 1994). The view zenith angle varies between ±55°, or about ±61° at the surface.

DESCRIPTION OF THE CLOUD ABSORPTION RADIOMETER (CAR)

The Cloud Absorption Radiometer (CAR) is a multispectral scanning radiometer developed at Goddard Space Flight Center, initially for measuring angular distribution of scattered radiation deep within a cloud layer - at selected wavelengths in the visible and near-infrared, and to determine the spectral single scattering albedo of clouds using a technique that avoids the difficulties of traditional radiometric observations (King et al., 1986). Because of its multiple viewing geometry, the CAR has since been used to measure bidirectional reflection distribution functions (BRDF) as described in studies by Tsay et al. (1998); Soulen et al. (1999), and Arnold et al. (1999). This is done using a plane that assumes a closed circular flight pattern (circle diameter ~ 3 km) over a uniform surface of interest (e.g., ocean, snow, tundra, etc.) at constant altitude, uniform speed, and a roll angle of ~20°. The CAR instrument, sampling in downward-imaging mode can be used to supplement the MODIS Airborne Simulator (MAS; King et al., 1996).

The CAR is now housed in the nose-cone of the University of Washington Convair CV-580 research aircraft, and was designed to operate from low to high altitude, and to scan through a plane defined by a scan angle of 190°, either from 5° before the solar zenith (point vertically upward in the skyward direction) to 5° past nadir (point vertically downward on the ground), in the starboard imaging mode; or from 5° above the horizon (skyline) on the right-hand side of the aircraft to 5° past the horizon on the left-hand of the aircraft, while in the downward imaging mode. The imaging mode is automatically changed by rotating the CAR through 90° around the aircraft.

The CAR has an Instantaneous Field of View (IFOV) of 1°. The optical system of the CAR is nondispersive, comprising a complex configuration of dichroic beam splitters and narrow band interference filters. The CAR has 13 optical channels represented by the central wavelengths: 0.3880, 0.4715, 0.6752, 0.8685, 1.0375, 1.2190, 1.2710, 1.5515, 1.6430, 1.7250, 2.0990, 2.2070 and 2.3025 μm.

DATA

We chose CAR Flight 1689, a low turbidity flight northwest of Brasilia, Brazil. The entire flight lasted a few hours, giving several thousand scans. The aircraft flew about 500 to 5000 meters above the ground during this flight. Accordingly, the footprint of the CAR scans is about 10 to 100 meters on the ground. We use some of these data to examine the relation $\rho_{0.47}(0.68) = k_0\, \rho_{2.1}$, where k_0 is a constant, for view angles from nadir to 65° off-nadir.

To find the correlation between reflectivity in the visible and 2.2 μm, we have analyzed data from Flight 1689 that represent a clean case from 1747 to 1751 UTC. The section selected represent data over ground sections that seemed uniform from visual inspection of the RGB composite images of the entire flight. With the plane traveling at a nominal speed of 80 m/s, and the mirror making 100 rpm, the flight section selected represents 400 scans spread over 19.2 km for view angles ranging from 5° before zenith to 5° after nadir. Since data is corrected continuously in channels 1–6 we have a sample every 0.6 seconds or after every 48 meters. If the filter wheel, representing channels 7-13, is locked in one channel, then data throughput is similar to channels 1–6 for the selected channel. If the filter wheel is set to rotate in each of the channels 7-13 after y number of scans, as it was in this case, then for each channel a sample is repeated every 4.8y seconds or after 364y m along the ground-track at the nominal plane speed of 80 m/s. This study required us to use data from the visible, channel 1 (0.472 μm) and 2 (0.675 μm), and near infrared, channel 12 (2.2 μm); so the number of data points is limited to the data from channel 12 within the time limits and distance in each of the flights.

RESULTS

Reflectance measurements in the 2.2 μm atmospheric window are least affected by most aerosol types (smoke, sulfates, etc.), whereas the effect is significant for measurements in the visible wavelengths, blue (0.472 μm) and red (0.675 μm). In order to test whether a relation exists between solar radiation at 2.2 μm and the visible (blue and red), we have plotted reflectance at 2.2 μm against reflectance at 0.472 μm and 0.672 μm for view angles between nadir (0°) and 65° (Fig. 1). During Flight 1689, located northwest of Brasilia between 1747 and 1751 UTC, the solar zenith angle $\theta_0 = 45.4°$, the solar azimuth angle $\phi_0 = 304.1°$, the aircraft heading H = 346.2°, and the height of the aircraft above the ground was 2450 m. Since the CAR mirror scans in a plane 90° to the right of the aircraft heading, the relative azimuth $\Delta\phi = 132.1°$. This means that the photons reflected by the surface-atmosphere system are backscattered from the target viewed by the CAR. The position of the aircraft charged from 13.18°S, 48.56°W to 13.36°S, 48.51°W, while its altitude varied by ~20 m. Clear weather was observed, and signs of haze were absent; therefore this flight can be characterized as a clean one with low aerosol concentration, cloud free conditions, and aerosol optical thickness $\tau_a = 0.08$, as measured by a sunphotometer located in the area.

Fig. 1a is a scatter plot of reflectance at 0.472 (0.675) μm and reflectance at 2.2 μm for a nadir view angle. Results of view angles from 1° to 10°, then 15°, 20°, 30°, 40°, 45°, 55°, and 65° in terms of slopes, intercepts and correlation coefficients are shown in Table 1. The slope of the plots gives the correlation and the intercept, the offset or the bias that may be a result of the inhomogeneity of the surface. For the blue reflectance, the slope is 0.169 at nadir, remains the same at 1°off-nadir, drops to 0.118 at 2° off-nadir, and fluctuates between the two values for most view angles. The slope drops to 0.102 at 55° and 0.090 at 65°. For all view angles between nadir and 65°, the intercept values vary from 0.02 to 0.07. For different instruments (Landsat TM and AVIRIS) and different time periods, Kaufman et al. (1997) obtained gradient values between 0.13 and 0.30, and intercepts between -0.006 and 0.013. In fact the slopes obtained for an AVIRIS dataset in July 1993, over Hagerstown, Maryland and New Jersey, are strikingly similar to the values reported in this study. Considering our data have not been corrected for atmospheric effects (absorption and scattering), it is noteworthy that our values are within the range of values reported in Table 1 of Kaufman et al. (1997), and different from his average of 0.24. What happens after atmospheric effects are removed is discussed elsewhere (Gatebe et al., 2000 – in preparation).

Let us now look at the correlation at 2.2 μm and 0.675 μm, shown in Fig. 1 as red circular symbols (see also Table 1). For all view angles the slope lies between 0.35 and 0.56, very similar to the range of values obtained by Kaufman et al. (1997) for Landsat and AVIRIS images. The intercepts are quite small; for most view angles the intercepts are in the range of ~0.001 and in a few cases in the range of 0.027, comparable to the intercepts obtained by Kaufman et al. (1997).

The above results are strikingly similar to Kaufman et al (1997) and seem to suggest that for the view angles tested, the reflectance $\rho_{0.472}$ and $\rho_{0.675}$ are predictable from $\rho_{2.1}$ using: $\rho_{0.472} = \rho_{2.1}/6$, which is a slight modification of Kaufman et al. (1997) and $\rho_{0.675} = \rho_{2.1}/2$, similar to Kaufman et al. (1997).

Would these relations hold for other conditions, for example different solar geometry and atmospheric conditions?

We have analyzed data from other sections of flight 1689 where conditions are different: between 1918 and 1923 UTC, solar zenith angle $\theta_0 = 65.5°$, solar azimuth $\phi_0 = 291.2°$, H = 181.9°, and $\Delta\phi = 19.3°$. For this situation, the photons reflected from the surface-atmosphere system are forward scattered from the target viewed by the CAR. Most of the other conditions remain the same: clear weather was observed, low aerosol concentration, cloud free conditions, and aerosol optical thickness $\tau_a = 0.08$. In the blue, at all angles, the slope lies between 0.038 and 0.11; and in the red, at all angles, except 55° whose slope is 0.19, the slopes lie between 0.23 and 0.39. Although the $\rho_{2.2}$ values are small (< 0.25), the slope doesn't seem to agree with Kaufman et al., (1997). Considering data in another flight section, between 1941 and 1945 UTC, θ_0= 65.5, ϕ_0=291.2°, and relative azimuth (ϕ) =17.3°, produces different results, with the slopes in the blue between 0.04 and 0.08 and those in the red between 0.18 and 0.28. These results show that despite the reflectance at 2.1 μm being small ($\rho_{2.1} < 0.25$), the ratio technique does not seem to hold when viewing in the forward direction. In a previous study, Brent et al. (1984), by simulating visible and near-infrared data from Advanced Very High Resolution Radiometer (AVHRR) data for a dark target, bare soil, and green-leaf biomass (low, medium, and high levels), showed that viewing in the backscatter direction has more constant radiance with increasing scan angle than viewing in the forward scattering direction. This probably explains the differences between backward and forward reflectance ratios.

ACKNOWLEDGEMENT

This research was supported by funding provided by the MODIS Science Team, the EOS Project Science Office, and NASA's Radiation Science Program.

REFERENCES.

Arnold, G. T., M. D. King, S. C. Tsay, J. Y. Li, and P. F. Soulen, "Airborne spectral measurements of surface-atmosphere anisotropy for Arctic sea ice and tundra," Int. J. Remote Sens., 1999, submitted.

Fraser, R. S., Y. J. Kaufman, and R. L. Mahoney, "Satellite measurements of aerosol mass and transport," Atmos. Environ., **18**, 2577-2584, 1992.

Holben, B. N., E. Vermote, Y. J. Kaufman, D. Tanré, and V. Kalb, "Aerosol retrieval over land from AVHRR data–Application for atmospheric correction," IEEE Trans. Geosci. Remote Sens., **30**, 212-222, 1992.

Husar, R. B., J. M. Prospero, and L. L. Stowe, "Characterization of tropospheric aerosols over the oceans with the NOAA advanced very high resolution radiometer optical thickness operational product," J. Geophys. Res., **102**, 16889-16909, 1997.

Kaufman, Y. J., A. E. Wald, L. A. Remer, B. C. Gao, R. R. Li and L. Flynn, "The MODIS 2.1-μm channel-correlation with visible reflectance for use in remote sensing of aerosol,, IEEE Trans. Geosci. Remote Sens., **35**, 1286-1298, 1997.

Kaufman, Y. J., R. S. Fraser, and R. A. Ferrare, "Satellite measurements of large –scale air pollution: Methods", J. Geophys. Res., **95**, 9895-9909, 1990.

Kaufman, Y. J. and C. Sendra, "Algorithm for automatic corrections to visible and near-IR satellite imagery," Int. J. Remote Sens., **9**, 1357-1381, 1988.

King, M.D., Y.J. Kaufman, D. Tanré, and T. Nakajima, "Remote sensing of aerosols from space: Past, present, and future," Bull. Amer. Meteor. Soc., **80**, 2229-2259, 1999.

King, M. D., M. G. Strange, P. Leone, and L.R. Blaine, "Multiwavelength scanning radiometer for airborne measurements of scattered radiation within clouds," J. Atmos. Oceanic Technol., **3**, 513-522, 1986.

King, M. D., W. P. Menzel, P. S. Grant, J. S. Myers, G. T. Arnold, S. E. Platnick, L. E. Gumley, S. C. Tsay, C. C. Moeller, M. Fitzgerald, K. S. Brown and F. G. Osterwisch, "Airborne scanning spectrometer for remote sensing of cloud, aerosol, water vapor and surface properties," J. Atmos. Oceanic Technol., **13**, 777-794. 1996

Soulen, P. F., M. D. King, S. C. Tsay, G. T. Arnold, and J. Y. Li,1999, "Airborne spectral measurements of surface-atmosphere anisotropy during the SCAR-A, Kuwait oil fire, and TARFOX experiments," J. Geophys. Res., 1999, in press.

Tsay, S. C., M. D. King, G. T. Arnold, and J. Y. Li, "Airborne spectral measurements of surface anisotropy during SCAR-B," J. Geophys. Res., **103**, 31943-31954, 1998.

TABLE 1: Slope, intercept, and correlation coefficient ® for view angles from nadir to 65° off-nadir computed from scatter plot of reflectance at blue (0.49 μm) and red (0.67 μm) against reflectance at 2.2 μm. For each view angle the number of values used in the computations are indicated.

View Angle	Points	Slope ± standard deviation		Intercept		R	
		Blue	Red	Blue	Red	Blue	Red
0	48	0.169± 0.008	0.445± 0.022	0.023	0.006	0.927	0.952
1	48	0.169± 0.008	0.503± 0.025	0.023	-0.002	0.899	0.917
2	51	0.118± 0.006	0.372± 0.017	0.030	0.015	0.894	0.917
3	51	0.128± 0.007	0.390± 0.021	0.028	0.011	0.917	0.929
4	51	0.117± 0.007	0.353± 0.019	0.030	0.017	0.876	0.868
5	51	0.148± 0.006	0.477± 0.026	0.026	0.001	0.864	0.884
6	51	0.140± 0.007	0.457± 0.020	0.026	0.002	0.850	0.925
7	49	0.110± 0.007	0.352± 0.018	0.031	0.017	0.840	0.900
8	51	0.130± 0.007	0.395± 0.022	0.029	0.012	0.879	0.896
9	50	0.121± 0.006	0.366± 0.017	0.030	0.016	0.867	0.868
10	51	0.153± 0.007	0.460± 0.022	0.026	0.004	0.879	0.907
15	51	0.128± 0.006	0.394± 0.020	0.029	0.009	0.891	0.896
20	50	0.154± 0.009	0.507± 0.039	0.028	-0.001	0.917	0.926
30	51	0.169± 0.010	0.563± 0.032	0.030	-0.009	0.921	0.924
40	51	0.178± 0.012	0.544± 0.035	0.034	-0.005	0.942	0.936
45	51	0.155± 0.009	0.468± 0.027	0.039	0.005	0.919	0.916
55	51	0.102± 0.005	0.354± 0.017	0.057	0.027	0.763	0.764
65	51	0.090± 0.004	0.312± 0.014	0.071	0.036	0.775	0.802